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Impacts of aluminum production: A cradle to gate investigation using life-cycle assessment

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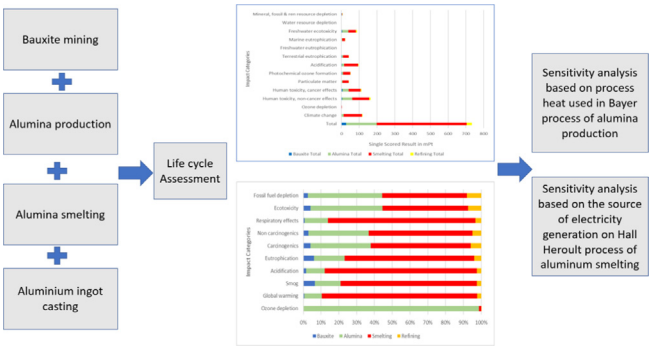
HIGHLIGHTS

- Conducted full LCA study on bauxite to aluminum production
- Aluminum smelting and refining causes the significant environmental effects.
- Significant environmental impact on climate change, acidification, and ecotoxicity
- Process heat consumption in Bayer process should be replaced by renewable energy.
- Alteration of electricity generation source for smelting can enhance sustainability.

GRAPHICAL ABSTRACT


Bauxite mining
Alumina production
Alumina smelting
Aluminium ingot casting
Life cycle Assessment
Sensitivity analysis based on process heat used in Bayer process of alumina production
Sensitivity analysis based on the source of electricity generation on Hall Heroult process of aluminum smelting

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ABSTRACT

In this study, a life-cycle assessment from the aluminum production processes is carried out by considering four major steps of aluminum production - bauxite mining from the ore, alumina production, smelting, and the ingot casting process of aluminum. The study considered the cradle to gate system to analyze and quantify the environmental impacts during aluminum production process from raw materials to the final finished product. The production input and output datasets are taken from the databases and eGrid reports and the analysis is carried out utilizing three different methods, namely the International Life-cycle Reference Data System (ILCD) method, the Tool for Reduction and Assessment of Chemicals and Other Environmental Impacts (TRACI) method, and the Cumulative Energy Demand (CED) method. The results show electricity consumption in aluminum smelting causes noteworthy environmental burdens among all the processes or materials involved. Residual fuel oil, diesel, and natural gas consumption during the alumina production is also a major contributor to environmental impacts. Sensitivity analysis is conducted to justify the variation of environmental impacts in proportion with the modes of electricity generation from different sources to be used for aluminum smelting. Further sensitivity analysis is carried out among the quantity of the fossil fuel used based on their sources for process heat generation during alumina production. According to the sensitivity analysis results, renewable energy integration or reducing the consumption of fossil fuels would be the promising alternative to reduce the environmental burdens associated with aluminum production.

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1. Introduction

Bauxite is the principal aluminum ore during primary aluminum production and mainly consists of aluminum hydroxide, alumina-silicates,

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Nomenclature

kg CO_2 eq	Carbon dioxide equivalent
kg CFC-11 eq	
Ozone Depletion Potential OZDP	kg CFC-11 eq
CTUh	Comparative Toxic Unit for human
Kg PM 2.5 eq	Unit for particulate matter
Kg NMVOC eq	non-methane volatile organic compounds equivalent
Molc H+ eq	
Mole of Hydrogen equivalent	
Molc N eq	Mole of Nitrogen equivalent
kg P eq	kilograms of Phosphorus equivalent
kg N eq	kilogram of Nitrogen equivalent
CTUe	Comparative Toxic Unit for ecosystems
M^3 H2O	The volume of water supply
kg Sb eq	kilogram of Antimony equivalent
kg SO_2 eq	Kilogram of sulfur di oxide equivalent
kg O_3 eq	Kilogram of ozone equivalent
MJ surplus	Characterized fossil fuel profile
MJ HHV	Higher heating value in mega joule
MJ LHV	Lower heating value in mega joule

and zinc oxide (Donoghue et al., 2014). Bauxite ore is found and mined in many countries including Australia, China, Brazil, New Guinea, and India. Australia has the largest resource and production of Bauxite (U.S. Geological Survey, 2018). Australia has around 30% of the global production of bauxite whereas they have the world's largest resources for them. China is currently the largest producer of aluminum producing a total of 19% of the world's production. Brazil holds the second largest position with 13% of the total world's production. More than 85% of the mined bauxite globally is converted into alumina to produce aluminum metal.

A thorough assessment is required to quantify the environmental effects of the aluminum production processes. For analyzing the environmental effects from a manufacturing process or a system of processes, the life-cycle assessment has been used as an effective tool for many years (Haque et al., 2014; Norgate and Haque, 2010). Four mandatory stages are applied during conducting a full LCA study: goal and scope definition, the data collection phase named life-cycle inventory, the analysis phase named life-cycle impact assessment, and the interpretation of the identified results (Farjana et al., 2019; Khasreen et al., 2009). The analysis in this methodology is conducted by identifying major input and output products, processes, raw materials, and emissions (Awuah-Offei and Adekpedjou, 2011). Combined production of metals are analyzed through allocation method where the allocation of metals in a process or a system of processes varies depending on their masses or market values (Curran, 2012; JRC European Commission, 2011).

From the previous studies on life-cycle analysis of aluminum processing technologies, Tan et al. considered four different case scenarios for impact assessment of aluminum billets. Their results reveal that environmental emissions could be significantly reduced by reducing the scrap metals. Reducing the scrap metals can also be equipped with an improvement in energy efficiency (Tan and Khoo, 2005). Nunez et al. researched life-cycle assessment of aluminum mining using two different regional datasets. The data sets are focused on a global scale and global minus China, while models are constructed on a cradle-to-gate life-cycle inventory model under six CML environmental impact categories. Their results reveal that the highest impact contribution is due to alumina refining and electrolysis due to the highest amount of energy consumption. However, their research does not show the impact analysis results in all environmental categories (Nunez and Jones, 2016). Parasvekas et al. discussed the environmental effects of aluminum production based on 29 different countries technology mix, heat mix, and electricity mix, which varies significantly from one country to another (Paraskevas et al., 2016). Grimaud et al. analyze the life-cycle impacts of the alumina recycling process in shredder cables plant in France. The research output from their study showed that huge environmental benefits of alumina recycling rather than primary aluminum production (Grimaud et al., 2016). Norgate et al. analyze and compare bauxite mining, iron mining, and copper mining processes and presents their key impact-analysis results (Norgate and Haque, 2010). Table 1 shows the comparison of significant LCA research based on bauxite and aluminum production and their limitations or gaps covered with the current research. This table show the research contribution of the present article.

There are some published work on the life-cycle assessment of some other metals and mining industries in recent years (Farjana et al., 2018a; Haque and Norgate, 2014, 2015; Norgate and Haque, 2010). This paper will identify the major process/materials accountable for environmental emissions in each stages of cradle-to-gate bauxite to aluminum production, that consists of four major mining processes as reported earlier. The paper starts with a brief introduction, then Section 2 gives a detailed overview of the aluminum production process. Section 3 illustrates the materials and methodologies followed for the detailed LCIA results. Section 4 discusses the life-cycle analysis results based on present research and compare the results with that one obtained from the previous literature. Section 5 summarizes and concludes the paper with some recommendations on ways to reduce some of the environmental impacts including results of the sensitivity analysis.

2. Bauxite to aluminum mining process

Bauxite is found in the earth as a combination of various minerals which is mined from various locations (Davis, 2001; Nuss and Eckelman, 2014; U.S. Geological Survey, 2018). All the mining areas are surveyed at the beginning to protect plants and vegetables by making proper management plans (Donoghue et al., 2014). In the second stage, scrapers and excavators are employed to remove overburden from the top of the ore. Depending on the depth of the rock ore, blasting can be chosen using scrapers and excavators. Then the bauxite is mined and loaded into the transport truck and send for crushing (Mudd, 2009). At the time, several pit mines could be employed for extraction. In the next stage, a crusher is used to break the ore down into smaller pieces for ease of transportation using conveyor belts. The crusher is made up of components like vibrating screen, sider, and jaw crusher. Fine material ores are passed through vibrating screens while large particles pass through the jaw crusher directly. After crushing, both materials are collected and passed to the conveyor belt. Through the conveyor belt, materials are passed to the refineries. At the last stage after mining, the topsoil and overburden are returned to the surface to protect the environment and to ensure proper seeding and planting (Donoghue et al., 2014; Bergsdal et al., 2004; U.S. Geological Survey, 2018; Zhang et al., 2016). The bauxite to the aluminum production process is described by Fig. 1.

After bauxite mining, the bauxite rock ores are crushed using grinding mills. Then ore conveyors are used to transporting the prepared aluminum oxide. Bauxite is processed to make aluminum oxide before it is processed further to make aluminum, which requires electrolysis (Haraldsson and Johansson, 2018; Murray, 1999). It is used in aluminum refineries to produce aluminum oxide from bauxite (Suppen et al., 2006). One tonne of alumina is produced from 2.9 t of bauxite. Bauxite residues from alumina production have long posed a problem of management and disposal (Rhamdhani et al., 2017). Regarding sustainability, original bauxite produces potential toxic substances and radioactive materials, even though the type of residue is dependent on the type of bauxite deposit. There have been numerous efforts for improving the existing process of aluminum production routes (Haraldsson and Johansson, 2018; Huda et al., 2017; Norton, 2014; Rhamdhani et al., 2017). Table 2 shows the bauxite and alumina production, reserve, and aluminum smelter production and capacity in the dominant

Table 1
Key findings and comparison among major LCA-related research on bauxite and aluminum production processes.

References	Software and methods	Key findings	Differences with the present study
Norgate and Haque (2010)	Australian indicator method with SimaPro software (the geographic region under consideration is Australia).	Assesses the energy and greenhouse-gas-impacts of the open-cut bauxite extraction method	Alumina production, smelting, and refining are not considered.
Nunez and Jones (2016)	CML method with Gabi software (the geographic regions are global and global minus China)	Assessed six major impact categories of the environment. The key finding is that alumina refining and electrolysis is the highest energy intensive process	Lacks impact analysis under impact categories like human toxicity which might be carcinogenic or non-carcinogenic, ecotoxicity, particulate matter, and the depletion of water-based resources. Also, did not analyze and compare the materials/inputs involved in the production processes, which better reveals the responsibility of energy consumption and greenhouse-gas emission.
Tan and Khoo (2005)	Sensitivity analysis using SimaPro software (the geographic region is Australia)	Five major impact categories are assessed and analyzed through sensitivity analysis based on transportation: global warming, human toxicity (air), acidification, resources, and bulk waste.	Few major impact categories are considered and did not analyze and compare the materials/inputs involved in the production processes.
Zhang et al. (2016)	Sensitivity analysis using Shandong LCIA method and LCA software (the geographic region is China)	Twelve major impact categories are assessed while sensitivity analysis is carried out based on energy contributors, among primary aluminum oxide, primary aluminum, and secondary aluminum.	Analysis of the materials/inputs involved in the production processes are missing.

countries for bauxite and aluminum production (U.S. Geological Survey, 2018).

3. Materials and methods

Life-cycle assessment assesses and quantifies the environmental impacts from a manufacturing process or a system of processes (Norgate and Haque, 2012). ISO 14040 has defined stages for calculating life-cycle assessment results: starting from the goal and scope definition, inventory created for LCA analysis, the impact assessment carried out based on the LCIA methods, and the discussion related to significant results (Curran, 2012; Farjana et al., 2018b).

3.1. Goal and scope definition

At the first step of assessing the impacts from aluminum production processes, the critical process steps/materials of aluminum production, comprising bauxite mining, alumina production, aluminum smelting, and aluminum ingot casting are identified. The goal is achieved by analyzing the cradle-to-gate life-cycle environmental impact of aluminum production. This research also compiles life-cycle inventory datasets from the EcoInvent database for bauxite mining, alumina refining, aluminum smelting, aluminum ingot casting which originate from the Environmental Protection Agency database eGrid (EPA, 2018). This research compiles and compares the life-cycle inventory datasets among the four process steps involved in aluminum ingot production. Furthermore, sensitivity analysis is carried out to show the importance of decreasing the use of fossil fuel consumption and increasing energy integration potential. All the emissions or impacts generated from the steps of ore mining (cradle) to final finished product (gate) are considered as the scope of this research. Cradle activities also include processes like extraction and transportation using different means up to the final delivery of product, along with the final waste emission. The input materials considered are residual fuel oil, gasoline, electricity, transportation by different means (train and ship). The output product is 1 kg of aluminum ingot product (functional unit). The unit can be chosen as 1 kg of aluminum ingot or 1 ton of aluminum ingot produced from aluminum production process. However, as in ILCD method the units are quantified based on kilogram carbon dioxide equivalent or kilogram sulfur dioxide equivalent, it is easier to understand and compare to use the product functional unit as kilogram. There are emissions towards air and water, which includes carbon dioxide, carbon monoxide, methane, nitrogen oxides, sulfur oxides, oils, detergents, and solid waste. The geographic region considered is the United States. In the previous LCA studies relating to the aluminum production processes, the geographic region covered was global, global minus China, China, and

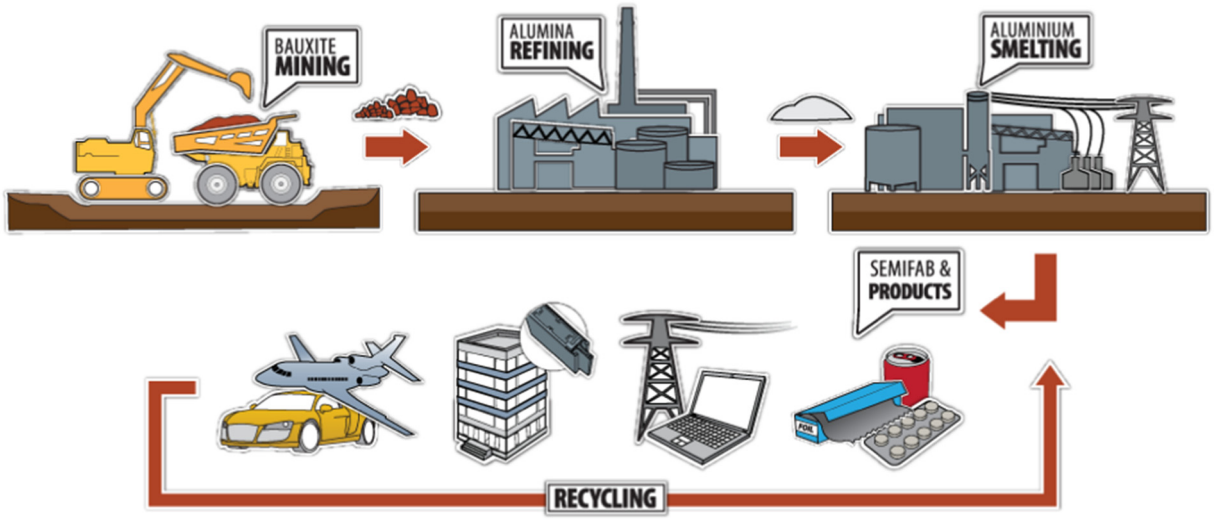

Fig. 1. Bauxite mining to aluminum ingot casting production flow.

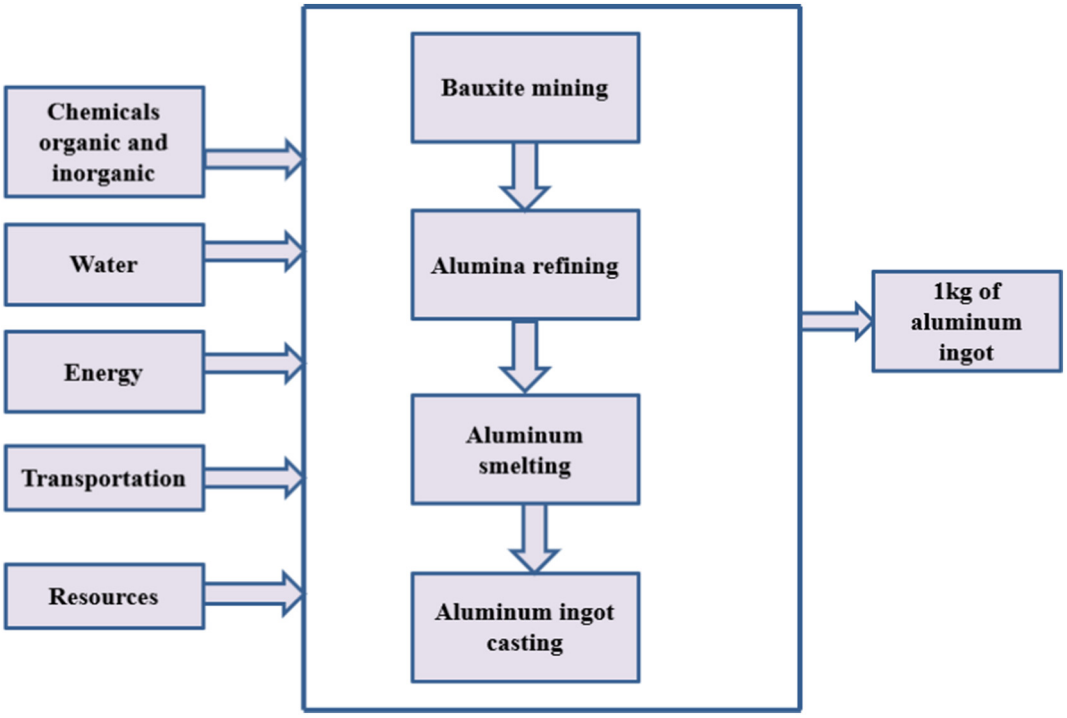

Fig. 2. System boundary to produce 1 kg of the aluminum ingot from bauxite to the aluminum production process.

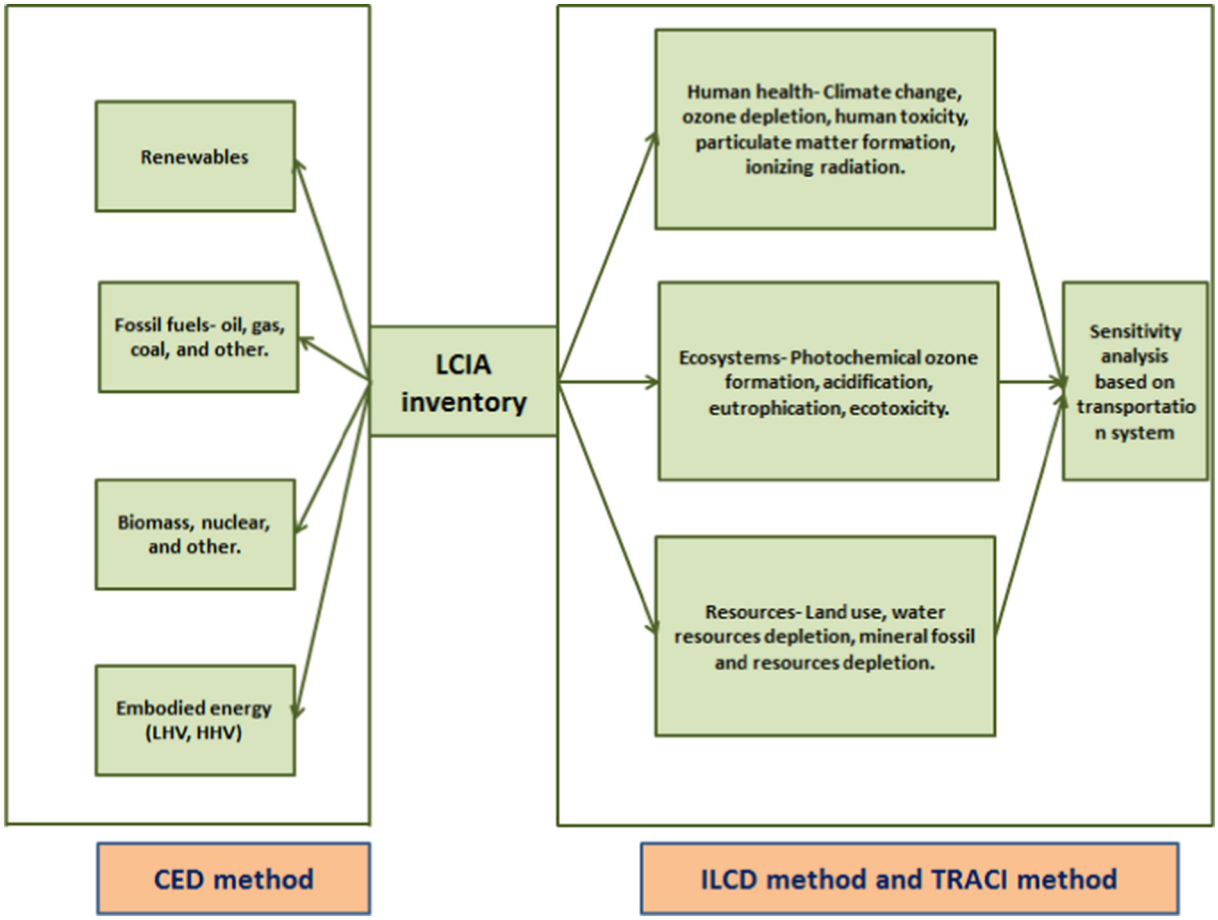
Renewables
Fossil fuels- oil, gas, coal, and other.
Biomass, nuclear, and other.
Embodied energy (LHV, HHV)
LCIA inventory
Human health- Climate change, ozone depletion, human toxicity, particulate matter formation, ionizing radiation.
Ecosystems- Photochemical ozone formation, acidification, eutrophication, ecotoxicity.
Resources- Land use, water resources depletion, mineral fossil and resources depletion.
Sensitivity analysis based on transportation system
CED method
ILCD method and TRACI method

Fig. 3. Analysis methodology utilized in this study for aluminum production processes (Farjana et al., 2019; Farjana et al., 2018b).

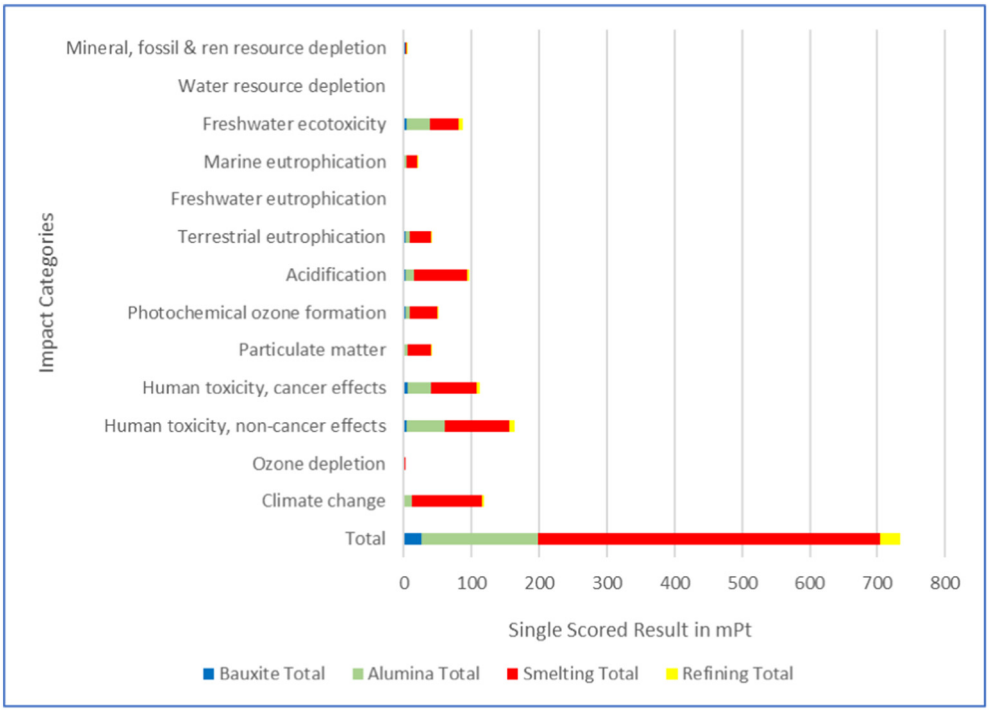

Fig. 4. Analysis results from the ILCD method for the aluminum production processes.

Australia. It is another exciting part of this research which is crucial to compare geographical and technical differences between aluminum production and their relative impacts from various countries in the world. Fig. 2 shows the process system boundary followed in this work.

3.2. Inventory analysis

Table 3 show the inventory details consists of material in use and emission materials. The material inputs considered are required for producing 1 kg of aluminum-ingot casting product from the beginning of bauxite mining, subdivided based on the process steps. Material outputs are 1 kg of aluminum-ingot casting product including any byproducts and the production wastes. Among the energy inputs considered are fuel oil required to produce mineral ore from the mining site, fossil fuels combusted in industrial boilers, electricity generated for use mostly in aluminum smelting and also in other processes, transportation systems including ocean freighter using diesel power. The output emissions consist of the final product that consists of 1 kg of aluminum ingot casting product, particle emissions to air, particle or metal-ion emissions to water, waste emissions. SimaPro software version 8.5 is utilized for this analysis. Similar approaches were followed in previous LCA studies (Farjana et al., 2018b; Mahmud et al., 2018c; Mahmud et al., 2018a)

3.3. Life-cycle impact assessment

In this section, the life-cycle impact assessment methodology and analysis results under various impact categories assessed through the ILCD method, TRACI method, and Cumulative energy demand method (CED) are presented in detail. The International Reference Life-cycle

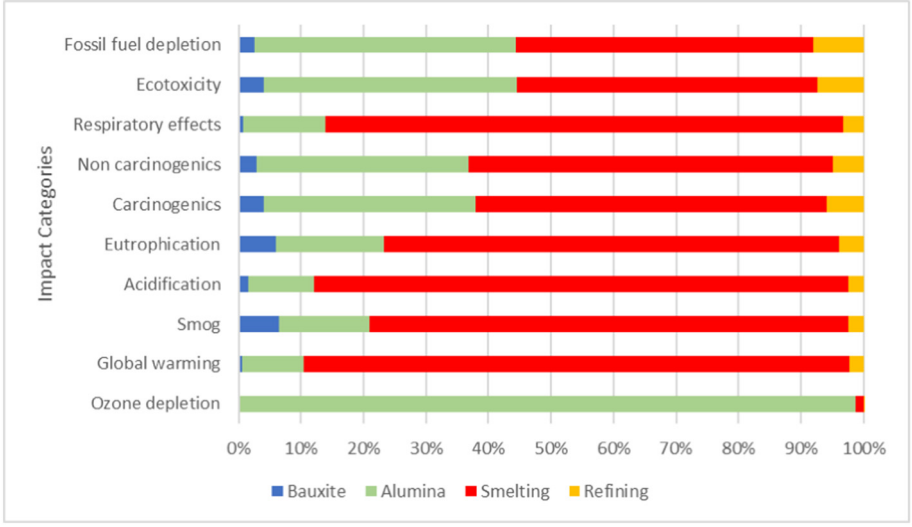

Fig. 5. Analysis results from TRACI method for aluminum production processes.

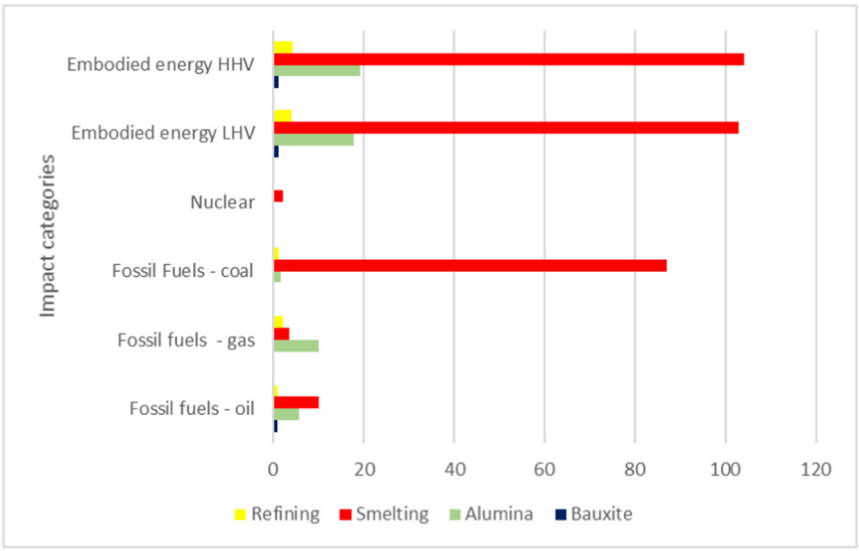

Fig. 6. Comparison between impact categories – Cumulative energy demand method.

Data System (ILCD) method which is developed in conjunction with the Joint Research Centre of the European Commission which assessed the environmental impact categories based on both midpoint indicators and endpoint indicators (Curran, 2012). The Tool for Reduction and Assessment of Chemicals and Other Environmental Impacts (TRACI) method is formulated by the Environmental Protection Agency (EPA) specifically for the United States (Das and Houtman, 2004). On the other hand, the cumulative energy demand method (CED) quantifies the amount of the consumption of energy throughout the entire life-cycle of the system of processes. This method is designed under eight major impact categories based on energy type, where normalization or weighted data is not considered for CED method (Hischier et al., 2010). In this research, both the TRACI and ILCD method are assessed for impact assessment though some of the impact categories overlapping. The TRACI method is designed for USA-based research, and the ILCD method is focused on the European continent. As the dataset for aluminum production processes is originated from USA-based companies here, environmental impacts based on the TRACI method is evident to be assessed. However, for comparison with other regions, the ILCD method is also used. Table 4 shows the impact categories under consideration here based on the TRACI method and the ILCD method. Fig. 3 shows the detailed results according to the method utilized in this work.

3.3.1. Analysis results of LCA based on ILCD method

The life-cycle impact analysis shows that, among the process steps of aluminum-ingot casting production, the aluminum smelting is the highest environmentally impactful process, which contributes mostly on ecotoxicity, human toxicity (cancer and non-cancer effects), climate change, and acidification. Table 5 and Fig. 4 describe the impact-analysis results from the ILCD method. Table 5 contains the characterized impact analysis results while Fig. 4 shows the normalized results where the characterization factors are for EC-JRC global (equal weighting). The climate change effect from smelting is 10.91 kg CO_2 eq, ozone depletion is 7.21E-11 kg CFC-11 eq, human toxicity non cancer effects is 2.22E-07 CTUh, human toxicity cancer effect is 1.25E-08 CTUh, photochemical ozone formation impact is 0.027 kg NMVOC eq, particulate matter impact is 2.59E-03 eq, acidification effect is 0.027 molc H+ eq, terrestrial eutrophication is 0.076 mol N eq, and freshwater ecotoxicity impact is 2.36 CTUe.

3.3.2. Analysis results of LCA based on TRACI method

The impact analysis using the TRACI method show that, among the process steps of aluminum-ingot casting production, the aluminum smelting is the highest environmentally impactful process which contributes mostly on global warming, smog, acidification, carcinogenic, and non-carcinogenic. Table 6 and Fig. 5 describe the impact-analysis results from the TRACI method. Table 6 contains the characterized impact analysis results while Fig. 5 shows the normalized results, where the characterization factors are for US-Canadian 2008. The global warming impact is 10.91 kg CO_2 eq, smog impact is 0.45 kg CO_2 eq, acidification potential is 0.075 kg SO_2 eq, the carcinogenic effect is 1.53E-08 CTUh, and non-carcinogenic effects is 1.53E-08 CTUh.

3.3.3. Analysis results of LCA based on cumulative energy demand (CED) method

The analysis methodology based on Cumulative Energy Demand (CED) provides the estimation of consumed fuel resources for each material/process within the analyzed system boundary. This method considers renewable fuels, fossil fuels, nuclear fuels, biomass, and all other types of energy resources. This method outlines the total amount of energy consumed based on low heating values and high heating values. Table 7 and Fig. 6 illustrate that coal is the main energy resources which are consumed during bauxite extraction, alumina refining, aluminum smelting, and the aluminum ingot casting production process. In the smelting process, the oil consumption is 10.06 MJ LHV, gas consumption is 3.68 MJ LHV, coal consumption is 87.15 MJ LHV, nuclear energy consumption is 2.15 MJ LHV, embodied energy LHV consumption is 103.04 MJ LHV, and embodied energy HHV is 104.11 MJ HHV.

Table 2
World resource and production of bauxite, alumina, and aluminum smelter (U.S. Geological Survey, 2018).

Country	Bauxite production	Alumina production	Reserves	Aluminum smelter production (Tonne)	Aluminum smelter year end capacity (Tonne)
China	68,000	72,300	1,000,000	32,600	44,500
Russia	5600	2800	500,000	3600	3900
India	27,000	6170	830,000	3200	3600
Canada		1570		3210	3270
US		1500	20,000	740	2000
Australia	83,000	20,600	6,000,000	1490	1720
Norway				1220	1550
Brazil	36,000	11,000	2,600,000	800	1400

Table 3
Detailed inventories of the processes considered in aluminum production (inputs and outputs).

	Bauxite	Alumina	Aluminum smelting	Aluminum ingot	Unit
Products					
Bauxite	1				kg
Alumina		1			kg
Aluminum, smelt			1		kg
Aluminum, primary, ingot				1	kg
Materials/fuels					
Residual fuel oil	1.25E-03	0.099	4.59E-04	1.86E-02	l
Gasoline	2.67E-04	2.3E-05	2.8E-04	7.3E-05	l
Diesel	4.3E-03	1.6E-03	1.8E-03	1.18E-04	l
Electricity	3.9E-04	0.109	1.54	0.21	kWh
Transport, train, diesel powered	0.349	0.486			tkm
Transport, ocean freighter, residual fuel oil powered	2.527	2.5			tkm
Transport, ocean freighter, diesel powered	0.28	0.28			tkm
Natural gas		0.225	7.6E-03	0.05	m3
Bituminous coal		8.59E-03			kg
Sodium hydroxide		0.0739			kg
Quicklime		0.0457			kg
Bauxite		2.64			kg
Liquefied petroleum gas			0.005	1.5E-03	l
Alumina			1.9		kg
Anode			0.455		kg
Aluminum, primary, smelt				1	kg
Emissions to air					
Carbon dioxide, fossil	7.9E-04		1.52	9.3E-04	kg
Carbon monoxide	3.2E-06		0.06	6E-06	kg
Methane	6.6E-06	1.7E-05	3.5E-04		kg
Nitrogen oxides	4E-05		1.1E-04	2.6E-05	kg
Dinitrogen monoxide	3.4E-07	2.2E-07			kg
NMVOC, non-methane volatile organic compounds	4.5E-07	4.7E-05	9.1E-04	3.8E-06	kg
Particulates, unspecified	0.0023	4.5E-04	4.75E-04	5.8E-05	kg
Sulfur oxides	1.1E-06			1.1E-05	kg
Hydrocarbons chlorinated		6.7E-10	1.2E-04	0.017	kg
Mercury		2.1E-08			kg
Carbonyl sulfide			1.12E-03		kg
Hydrogen cyanide			3.7E-05	5.3E-05	kg
Hydrogen fluoride			6.2E-04	2.3E-06	kg
Ethane, hexafluoro-, HFC-116			2.28E-05		kg
PAH, polycyclic aromatic hydrocarbons			1.15E-04		kg
Chlorine				1.8E-05	kg
Fluorine				1.9E-05	kg
Lead				9.4E-09	kg
Metals, unspecified				1.6E-07	kg
Organic substances, unspecified				1.1E-05	kg
Emissions to water					
Detergents, unspecified	2.5E-09		5.9E-07	1.5E-08	kg
Suspended solids, unspecified	2.1E-07	1E-05	7.6E-05	1.8E-04	kg
Nitrogen	6.5E-10		4.9E-07		kg
Oils, unspecified	1.9E-09	3.9E-07	9.9E-06	2.3E-05	kg
Phosphate	2.5E-09				kg
Suspended solids, unspecified	1.5E-08	1.3E-04	6E-05	6.7E-05	kg
Acids, unspecified		6.1E-05			kg
BOD5, Biological Oxygen Demand		6.1E-15	9.1E-06	4.1E-05	kg
Calcium		5.8E-06			kg
Chloride		7.6E-06	8.4E-06	7.888E-06	kg
COD, Chemical Oxygen Demand		4.6E-05	7.9E-05	2.1E-04	kg
Fluoride		7.9E-07	5.1E-05	2.7E-06	kg
Iron		1.6E-08	2.2E-06	8.6E-07	kg
Mercury		6.1E-10	4.0E-10	1.4E-11	kg
Metallic ions, unspecified		6.9E-05	8.2E-06	2.6E-06	kg
Phenol		3.9E-10	1.8E-07	1.2E-09	kg
Sodium		1.96E-03	6.2E-06		kg
Sulfate		1.75E-03			kg
Ammonium, ion			5.7E-07	3.6E-07	kg
Organic compounds (dissolved)			1.3E-05	1.3E-05	kg
Hydrocarbons, unspecified			4.8E-09		kg
Lead			4.6E-09	3.2E-09	kg
Cyanide				1.7E-09	kg
Sulfur				5.7E-07	kg
Waste to treatment					
Dummy disposal, solid waste	0.136	1.125	0.059	0.021	kg

Table 4
Impact categories from TRACI method and the ILCD method.

Impact category	TRACI method	ILCD method
CC (Climate change)	✓	✓
OD (Ozone depletion)	✓	✓
HTNC (Human toxicity, non-cancer effects)	✓	✓
HTC (Human toxicity, cancer effects)	✓	✓
PM (Particulate matter)		✓
POF (Photochemical ozone formation)		✓
AP (Acidification potential)	✓	✓
TE (Terrestrial eutrophication)		✓
FE (Freshwater eutrophication)		✓
ME (Marine eutrophication)	✓	✓
FE (Freshwater ecotoxicity)	✓	✓
WRD (Water resource depletion)		✓
MFRED (Mineral, fossil & ren resource depletion)	Fossil fuel depletion	✓
SG (Smog)	✓	
RE (Respiratory effects)	✓	

3.4. Sensitivity analysis for alumina production

This analysis is carried out based on the impact assessment results of the alumina production process, that residual fuel oil, diesel, and natural gas used to produce process heat in the Bayer process are mainly responsible for the environmental emissions here. The sensitivity analysis conducted here contains three scenarios including the base scenario. The scenarios were considered arbitrarily. The results show valuable information on how the impact numbers change due to change of the fuel type. The analysis results are presented in Table 8.

Case 1. Base case scenario that contains residual fuel oil 0.09931 l, diesel 0.00166 l, and natural gas 0.22512 m^3.

Case 2. The consumption of residual fuel oil is decreased by 50% which is replaced by diesel, natural gas consumption remains unchanged.

Case 3. The consumption of residual fuel oil is increased by 50% which is replaced by diesel, natural gas consumption remains unchanged.

The analysis results indicate that reducing the utilization of residual fuel oil and the natural gas helps to increase the sustainability indicators of the alumina production process. Scenario 2 shows comparatively positive result rather than scenario 1 and scenario 3. This sensitivity analysis result gives a better insight into the source of process heat generation in the Bayer process of alumina production. The integration of renewable energy generation sources in the Bayer process can be a good option in the future to reduce the environmental burdens generated from the Bayer process. However, the feasibility of integrating such a system is not proven yet and still undergoing significant research and development process. Solar industrial process heating systems are already in operation for many low temperatures, medium temperature, and high-temperature processes of the world. To integrate a successful solar system, design optimization based on solar collector system is a key step. The integration feasibility is also dependent on the geographic location of the plant to avail solar heat throughout the year. Process heat storage system with high energy efficiency is also mandatory to ensure a continuous supply of process heat during after hours (Farjana et al., 2018c, 2018d, 2018e, 2018f; Mahmud et al., 2018b).

3.5. Sensitivity analysis for alumina smelting

This analysis is carried out based on the Hall-Heroult process of alumina smelting based on the source of electricity generation. In the base case, the electricity supplied in the alumina smelting plant in United States in a combination of electricity generated by bituminous coal (0.346 kWh), nuclear power generated at plant (0.0086 kWh), hydropower generated at plant (0.639 kWh), diesel-powered (0.00118 kWh), and natural gas powered (0.00446 kWh) required to produce unit amount of alumina in smelting plant. This analysis is based on five cases.

Case 1. Base case scenario with the electricity mix used in alumina smelting zone in the US, which would vary from one smelting plant to another.

Case 2. The electricity required for the alumina smelting is supplied by a nuclear power plant. The inventory data for the nuclear power plant is collected based on US-based location. To produce 1 kWh of electricity, 3.04E-06 kg uranium is used here. The dataset is originated from the USLCI database, which is integrated with SimaPro. It is assumed that electricity required for smelting is supplied using nuclear power plant and no other sources have been used.

Case 3. The electricity required for the alumina smelting is supplied by hydropower plant. The inventory datasets for pumped storage hydropower plant located in the US is considered for calculation here, where the high voltage electricity and other materials are used in hydropower plant to generate and supply electricity to be used in aluminum smelting. The heat waste emission is 1.55 MJ.

Case 4. The electricity required for the alumina smelting is produced from a solar photovoltaic power plant located in the US. The solar PV plant is made up of different kinds of solar collectors and other materials to supply electricity to the aluminum smelting process. The heat waste emission 0.25 MJ.

Case 5. The electricity required for the alumina smelting is produced from a natural gas-based power plant located in the US, while the inventory datasets are originated from USLCI and EcoInvent database integrated with SimaPro. Processed natural gas and different modes of transportation are used in a natural gas-based power plant to supply electricity in aluminum smelting plant.

Table 5
LCIA results from ILCD method (using SimaPro software version 8.5).

Impact category	Unit	Bauxite	Alumina	Smelting	Refining
CC (Climate change)	kg CO_2 eq	0.079	1.23	10.91	0.27
OD (Ozone depletion)	kg CFC-11 eq	2.74E-12	1.09E-08	7.21E-11	3.19E-12
HTNC (Human toxicity, non-cancer effects)	CTUh	1.07E-08	1.29E-07	2.22E-07	1.86E-08
HTC (Human toxicity, cancer effects)	CTUh	1.01E-09	6.42E-09	1.25E-08	1.05E-09
PM (Particulate matter)	kg PM2.5 eq	2.54E-05	4.45E-04	2.59E-03	1.07E-04
POF (Photochemical ozone formation)	kg NMVOC eq	1.6E-03	4.4E-03	0.027	7.6E-04
AP (Acidification)	molc H+ eq	1.4E-03	0.011	0.065	2.6E-03
TE (Terrestrial eutrophication)	molc N eq	6.4E-03	0.014	0.076	2.3E-03
FE (Freshwater eutrophication)	kg P eq	8.25E-10	0	0	0
ME (Marine eutrophication)	kg N eq	5.9E-04	1.3E-03	6.9E-03	2.18E-04
FE (Freshwater ecotoxicity)	CTUe	0.2	1.96	2.36	0.36
WRD (Water resource depletion)	m^3 water eq	0	4E-05	0	0
MFRRD (Mineral, fossil & ren resource depletion)	kg Sb eq	8.71E-06	2.33E-07	1.56E-06	4.61E-08

Table 6
LCIA results from TRACI method (using SimaPro software version 8.5).

Impact category	Unit	Bauxite	Alumina	Smelting	Refining
		Total	Total	Total	Total
OD (Ozone Depletion)	kg CFC-11 eq	3.02E-12	1.21E-08	1.48E-10	4.32E-12
GWP (Global Warming Potential)	kg CO_2 eq	0.08	1.23	10.91	0.28
SG (Smog)	c	0.038	0.085	0.45	0.014
AP (Acidification Potential)	kg SO_2 eq	1.3E-03	9.3E-03	0.075	2.16E-03
EP (Eutrophication Potential)	kg N eq	7.06E-05	2.03E-04	8.5E-04	4.64E-05
CE (Carcinogenic Effects)	CTUh	1.09E-09	9.23E-09	1.53E-08	1.61E-09
NCE (Non-carcinogenic Effects)	CTUh	1.07E-08	1.29E-07	2.22E-07	1.86E-08
RE (Respiratory effects)	kg PM2.5 eq	2.17E-05	4.18E-04	2.6E-03	1.02E-04
ET (Ecotoxicity)	CTUe	0.2	1.99	2.37	0.36
FFD (Fossil fuel depletion)	MJ surplus	0.15	2.49	2.83	0.48

Table 9 showed that solar photovoltaic plants used for electricity supply in the alumina smelting could reduce the environmental effects. The solar-powered alumina smelting can reduce climate change effects, human toxicity (cancer), human toxicity (non-cancer), ecotoxicity impacts, acidification, and mineral resources depletion. The nuclear power plant can be a good alternative to the solar photovoltaic plant but have minimal effects to reduce environmental impacts in ozone depletion, freshwater eutrophication, and freshwater ecotoxicity. Scenario 2 (nuclear power plant) and scenario 4 (solar photovoltaic plant) are better than the scenario 1 (base case scenario). On the other hand, hydropower plant-based electricity supply and electricity supplied from natural gas are the worst options in comparison with the present electricity mix in alumina smelting plant. So, reducing the consumption of hydropower and natural gas-based power could reduce environmental effects (Mahmud et al., 2018a, b, c, d). In base case scenario, the climate change effect from smelting is 10.91 kg CO_2 eq, ozone depletion is 7.21E-11 kg CFC-11 eq, human toxicity non cancer effects is 2.22E-07 CTUh, human toxicity cancer effect is 1.25E-08 CTUh, photochemical ozone formation impact is 0.027 kg NMVOC eq, particulate matter impact is 2.59E-03 eq, acidification effect is 0.027 molc H+ eq, terrestrial eutrophication is 0.076 molc N eq, and freshwater ecotoxicity impact is 2.36 CTUe. After the integration of nuclear power plant to supply electricity in smelting plant, the climate change effect from smelting is 5.26 kg CO_2 eq, ozone depletion is 3.86E-09 kg CFC-11 eq, human toxicity non cancer effects is 1.18E-07 CTUh, human toxicity cancer effect is 8.65E-09 CTUh, photochemical ozone formation impact is 8.9E-03 kg NMVOC eq, particulate matter impact is 4.18E-04 eq, acidification effect is 9.9E-03 molc H+ eq, terrestrial eutrophication is 0.01 molc N eq, and freshwater ecotoxicity impact is 2.56 CTUe.

Overall, the environmental burden decreases in all categories except for freshwater ecotoxicity. In scenario 4, climate change effect from smelting is 6.1 kg CO_2 eq, ozone depletion is 1.07E-07 kg CFC-11 eq, human toxicity non cancer effects is 3.06E-07 CTUh, human toxicity cancer effect is 8.95E-08 CTUh, photochemical ozone formation impact is 0.01 kg NMVOC eq, particulate matter impact is 4.9E-03 eq, acidification effect is 8.18E-03 molc H+ eq, terrestrial eutrophication is 0.018 molc N eq, and freshwater ecotoxicity impact is 6.11 CTUe. Same as scenario 2, the freshwater ecotoxicity increases after integrating solar photovoltaic plant. In the case of Case 3, electricity supplied by hydropower plant, climate change effect from smelting is 21.87 kg CO_2 eq, ozone depletion is 4.6E-07 kg CFC-11 eq, human toxicity non cancer effects is 5.58E-07 CTUh, human toxicity cancer effect is 2.38E-07 CTUh, photochemical ozone formation impact is 0.044 kg NMVOC eq, particulate matter impact is 5.7E-03 eq, acidification effect is 0.11 molc H+ eq, terrestrial eutrophication is 0.135 molc N eq, and freshwater ecotoxicity impact is 5.64 CTUe.

4. Discussion

This section compares the comparative impacts from the processes involved in aluminum production processes. Fig. 7 shows a comparison among the input materials and chemicals for bauxite mining. Fig. 8 shows a comparison for the alumina refining process. Fig. 9 does the same for aluminum smelting, and Fig. 10 describes the comparative analysis for aluminum ingot casting production processes.

It is evident from the analysis results that carbon-di-oxide in the air, in fossil and biogenic, plays a crucial role in global warming, out of which, fossil-based carbon-di-oxide contributes the most. The most significant contributor for ozone layer depletion might be the vast quantity of chlorofluorocarbons emitted by the combustion of residual fuel oils. From the analysis of the inventory results, methane, dichloro difluoro, CFC 12 is the dominant element contributing to ozone depletion. A similar role is observed by ethane 1,1,1-trichloro, HCH 140. Analyzing the inventory results, ammonia, chemical oxygen demands (COD) and nitrogen oxides are responsible for these impacts. Analyzing the inventory results showed that fluoride, barium, beryllium, copper, nickel, and selenium are responsible for ecotoxicity effects. For the categories of aquatic ecotoxicity, barium is responsible while for terrestrial ecotoxicity; beryllium is the main point of emission. Analyzing the inventory results cadmium, arsenic, barium, and selenium emitted is mainly responsible for human toxicity. Other emissions are chromium, barium, and mercury.

From alumina production process, residual fuel oil consumption and from aluminum smelting, electricity consumed for aluminum smelting is mainly responsible for notable environmental impacts. Table 10 shows the comparison among the LCIA results obtained from this research and previous LCIA studies focused on aluminum production processes.

Table 10 shows a comparison with the previous LCA study regarding aluminum production, which was based on the global region and global minus China. The study conducted by Nunez et al. was based on datasets from the International Aluminum Association (IAI), where analysis was done by Gabi software by using the CML method in 6 midpoints indicator-based impact categories. The comparative analysis from Table 10 illustrates that aluminum production in the United States is much better than the rest of the world regarding fossil-fuel depletion but somewhat harmful to climate change. Also, they identify the alumina refining and electrolysis process to contribute most to the greenhouse gas effects while in the United States, alumina smelting is impactful on global warming. In another study, life cycle impact assessment of based on different region is conducted. The study considered five different scenarios. In scenario 1, bauxite mining, alumina

Table 7
LCIA results using cumulative energy demand method.

Impact category	Unit	Bauxite	Alumina	Smelting	Refining
Fossil fuels - oil	MJ LHV	0.98	5.75	10.06	0.95
Fossil fuels - gas	MJ LHV	0.042	9.97	3.68	2.02
Fossil Fuels - coal	MJ LHV	0.03	1.76	87.15	1.05
Nuclear	MJ LHV	9.2E-03	0.26	2.15	0.038
Embodied energy LHV	MJ LHV	1.067	17.75	103.04	4.07
Embodied energy HHV	MJ HHV	1.13	19.19	104.11	4.35

Table 8
Sensitivity analysis results based on fuel consumption in alumina production.

Impact category	Unit	Case 1	Case 2	Case 3
CC (Climate change)	kg CO_2 eq	1.23	1.20	1.23
OD (Ozone depletion)	kg CFC-11 eq	1.09E-08	1.09E-08	1.09E-08
HTNC (Human toxicity, non-cancer effects)	CTUh	1.29E-07	1.28E-07	1.29E-07
HTC (Human toxicity, cancer effects)	CTUh	6.42E-09	6.17E-09	6.41E-09
PM (Particulate matter)	kg PM2.5 eq	4.45E-04	4.28E-04	4.45E-04
POF (Photochemical ozone formation)	kg NMVOC eq	4.44E-04	4.16E-04	4.44E-04
AP (Acidification)	molc H+ eq	0.011	0.011	0.011
TE (Terrestrial eutrophication)	molc N eq	0.014	0.013	0.014
FE (Freshwater eutrophication)	kg P eq	0	0	0
ME (Marine eutrophication)	kg N eq	1.3E-03	1.2E-03	1.3E-03
FE (Freshwater ecotoxicity)	CTUe	1.97	1.92	1.96
WRD (Water resource depletion)	m^3 water eq	4E-05	4E-05	4E-05
MFRRD (Mineral, fossil & ren resource depletion)	kg Sb eq	2.33E-07	2.31E-07	2.33E-07

Table 9
Sensitivity analysis results based on the source of electricity consumed in the alumina smelting process.

		Case 1	Case 2	Case 3	Case 4	Case 5
Impact category	Unit	Base case	The case with a nuclear power plant	The case with a hydropower plant	The case with solar photovoltaic plant	The case with natural gas-based power plant
CC (Climate change)	kg CO_2 eq	10.91	5.26	21.87	6.1	16.61
OD (Ozone depletion)	kg CFC-11 eq	7.21E-11	3.86E-09	4.6E-07	1.07E-07	8.36E-07
HTNC (Human toxicity, non-cancer effects)	CTUh	2.22E-07	1.18E-07	5.58E-07	3.06E-07	7.13E-07
HTC (Human toxicity, cancer effects)	CTUh	1.25E-08	8.65E-09	2.38E-07	8.95E-08	2.45E-08
PM (Particulate matter)	kg PM2.5 eq	2.59E-03	4.18E-04	5.7E-03	4.9E-03	5.6E-03
POF (Photochemical ozone formation)	kg NMVOC eq	0.027	8.9E-03	0.044	0.01	0.026
AP (Acidification)	molc H+ eq	0.065	9.9E-03	0.11	8.18E-03	0.13
TE (Terrestrial eutrophication)	molc N eq	0.077	0.011	0.135	0.018	0.05
FE (Freshwater eutrophication)	kg P eq	0	1.03E-07	1.7E-04	3.35E-04	3.12E-06
ME (Marine eutrophication)	kg N eq	6.9E-03	1.03E-03	0.012	1.71E-03	4.8E-03
FE (Freshwater ecotoxicity)	CTUe	2.36	2.56	5.64	6.11	16.41
WRD (Water resource depletion)	m^3 water eq	0	1.29E-06	0.094	9.7E-03	7.27E-05
MFRRD (Mineral, fossil & ren resource depletion)	kg Sb eq	1.56E-06	6.12E-05	3.49E-07	3.49E-07	2.06E-06

production, smelting, refining, and ingot casting all are done in the plants located in China. In scenario 2, bauxite mining and alumina production are done in Oceania while rest are done in China. In scenario 3, the bauxite mine is in South America while rest are located and completed in Europe. In scenario 4, bauxite mining and alumina production are done in Oceania, while rest is done in the Gulf Cooperation Council. In scenario 5, the bauxite mine is in South America, alumina production plant is in North America, and rest is done in Canada. According to their analysis, according to their region based LCIA conducted for an aluminum production system, the lowest environmental burden is imposed by scenario 5 (plants located in South America, North America, and Canada). On the other hand, the highest environmental impact is imposed by scenario 5, while all the manufacturing processes are held in China (International Aluminum, 2017; Nunez and Jones, 2016). From the present research, the large volume of electricity consumed in aluminum smelting and residual fuel oil consumption in alumina production

Table 10
The LCIA results of this research and previous literature work.

Impact category	Unit	Global (Nunez and Jones, 2016)	Global minus China (Nunez and Jones, 2016)	This research
AP (Acidification)	kg SO_2 eq	0.13	0.090	0.22
FFD (Fossil fuel depletion)	MJ surplus	163	109	23.23
FE (Freshwater eutrophication)	kg P eq	0.011	5.3E-03	1.47E-08
CC (Climate change)	kg CO_2 eq	16.5	10.8	30.63
OD (Ozone depletion)	kg CFC-11 eq	2.9E-10	2.8E-10	6.31E-08
CE (Carcinogenic Effects)	CTUh			8.1E-08
NCE (Noncarcinogenic Effects)	CTUh			1.4E-06
SG (Smog)	kg O_3 eq			2.08
RE (Respiratory effects)	kg PM2.5 eq			0.008
POF (Photochemical ozone formation)	Kg NMVOC eq			0.109
MFRRD (Mineral, fossil & ren resource depletion)	Kg Sb eq			1.6E-04

Table 11
Summary of the results for alumina production and smelting process from this research.

Impact categories	Unit	Alumina smelting			Alumina production	
		Base case	Scenario for electricity produced from nuclear power plant	Scenario for electricity produced from solar photovoltaic power plant	Base case	Scenario for reduced residual fuel oil consumption replaced by diesel
Climate change	kg CO_2 eq	10.91	5.26	6.1	1.23	1.20
Human toxicity-cancer effects	CTUh	1.25E-08	8.65E-09	8.95E-08	6.42E-09	6.17E-09
Human toxicity-non cancer effects	CTUh	2.22E-07	1.18E-07	3.06E-07	1.29E-07	1.28E-07
Acidification	Molc H+ eq	0.065	9.9E-03	8.18E-03	0.011	0.011
Freshwater Ecotoxicity	CTUe	2.36	2.56	6.11	1.97	1.92

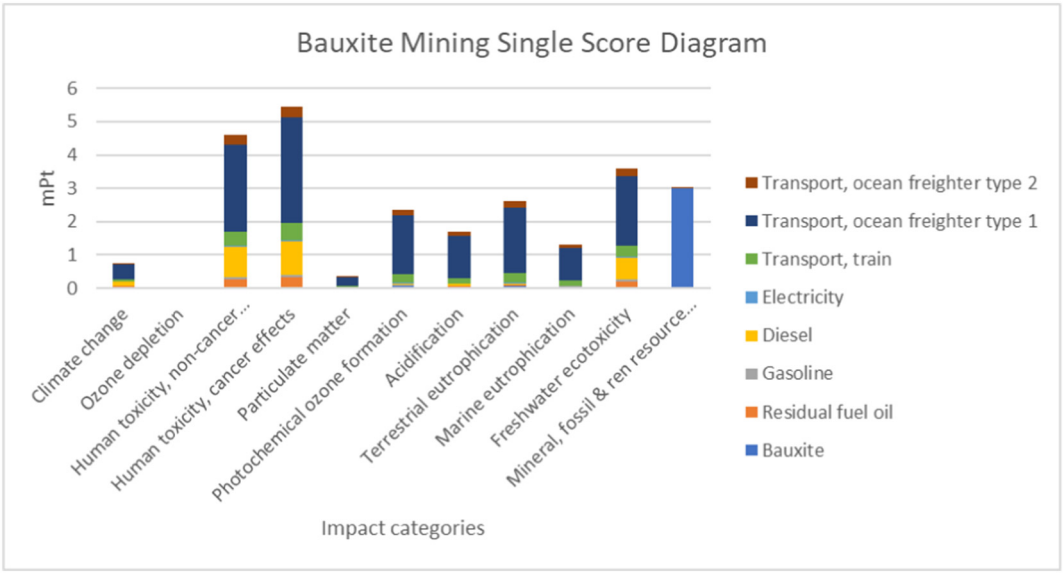

Fig. 7. Comparative analysis for bauxite mining process (single scored result).

is the most harmful from overall aluminum production processes. Due to the enormous amount of electricity consumed in the smelting process, this one effect solely on greenhouse-gas emissions, and is also responsible for polluting water species. Though significant hazards happen from bauxite mining due to soil erosion and sedimentation, noise, dust, the release of minerals and naturally occurring impurities,

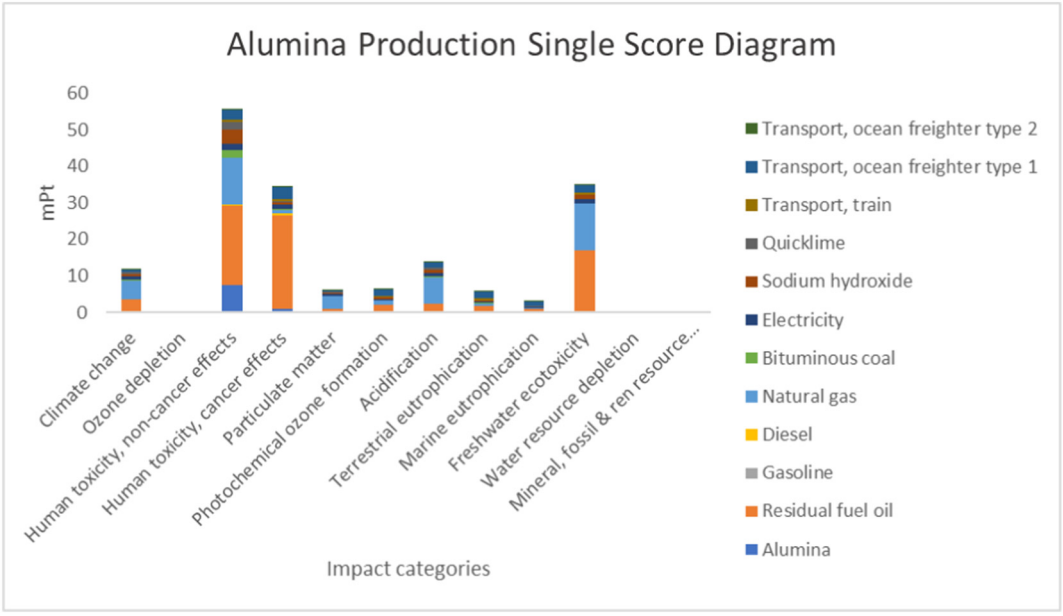

Fig. 8. Comparative analysis for the alumina production process (single scored result).

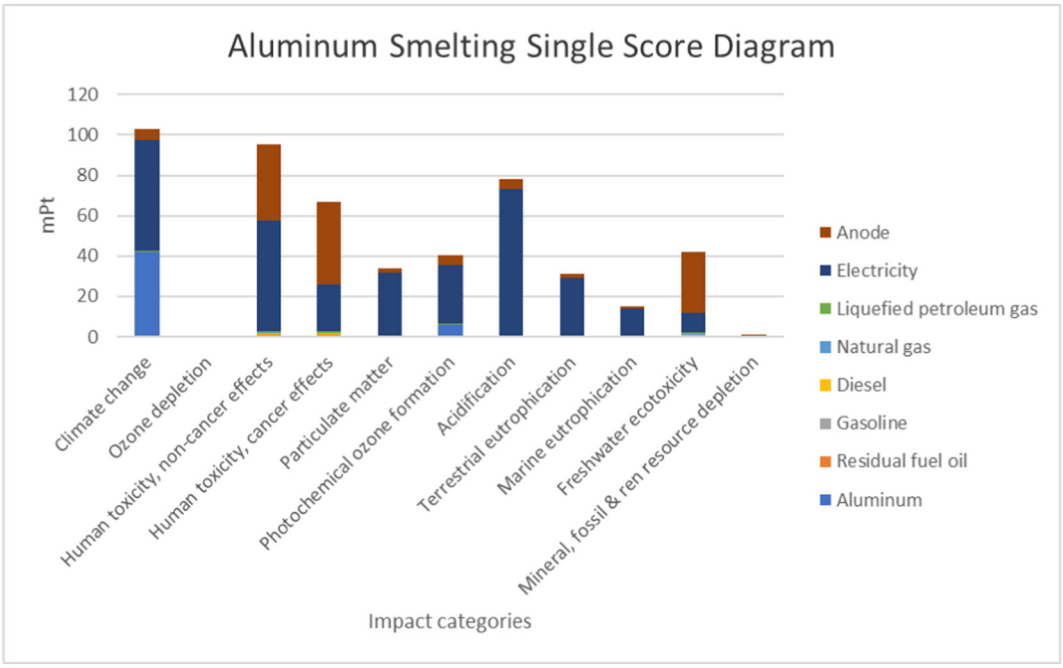

Fig. 9. Comparative analysis for the aluminum smelting process (single scored result).

human health is affected mainly by long and short-term exposure through physical, chemical or biological hazards.

In summary, from this research it is evident that the aluminum production process impacts largely on climate change, human toxicity (cancer effects), human toxicity (non-cancer effects), acidification potential, and freshwater ecotoxicity. The key reason for high environmental emission from smelting process is electricity consumed during the smelting operations. The sensitivity analysis results show that the impact due to large scale electricity consumption can significantly be reduced by altering the electricity generation source. The sensitivity analysis considered five scenarios including the base case scenario. Results showed that if solar photovoltaic plant or nuclear power plant can be used to supply electricity for alumina smelting process, it can significantly lessen the environmental emissions under the impactful categories (climate change, human toxicity- cancer effects, human toxicity- non-cancer effects, acidification potential, and freshwater ecotoxicity). Considerable amount of process heat is being consumed during alumina production through the Bayer process. The sensitivity analysis based on reducing the process heat consumption using residual fuel oil is presented in this research, which also indicates that alteration of process heat generation source would be highly beneficial to reduce environmental burdens associated with Bayer process. The results are briefly presented in the Table 11 below for the significant impact categories.

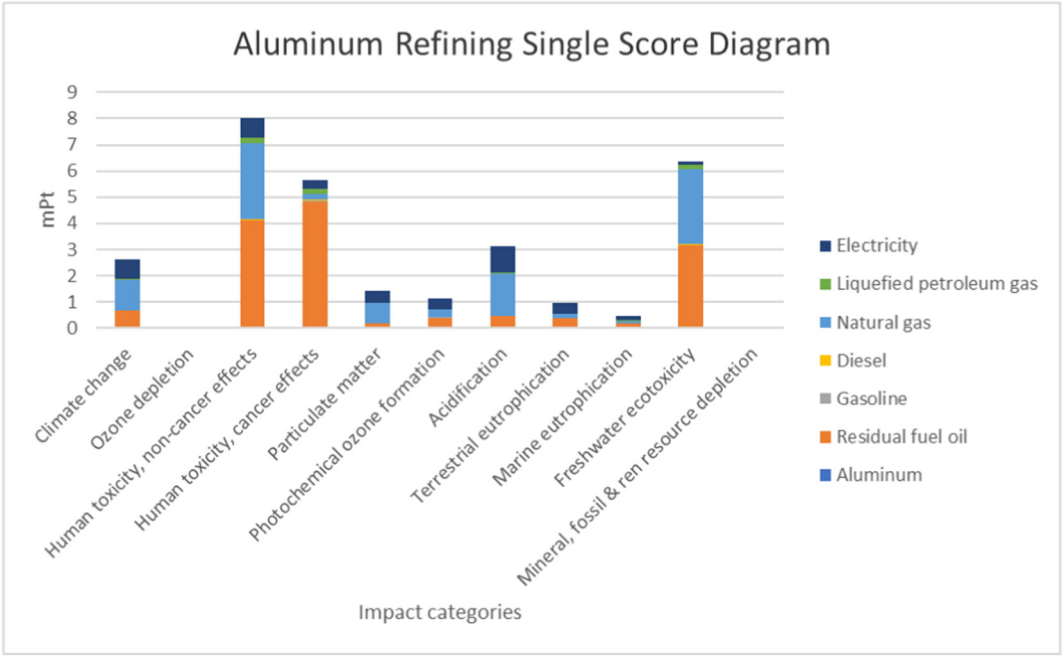

Fig. 10. Comparative analysis for the aluminum ingot casting process (single scored result).

5. Conclusion

A cradle-to-gate system is considered for bauxite extraction to aluminum-ingot casting production process to analyze the environmental impacts caused by the segments of inputs and materials used for aluminum processing. In this study, aluminum production, the aluminum supply chain production from bauxite mining to alumina refining, alumina recycling process, aluminum production routes by countries are analyzed through life-cycle assessment. Among the six categories (global warming, ozone formation, acidification, eutrophication, ecotoxicity, and human toxicity), the electricity consumed in the alumina smelting is the most significant contributor to environmental impacts. The primary reasons behind the environmental loads associated are the electricity generation resources and the enormous amount of electricity required for smelting. Also, process heat required for the alumina production is another major contributor of greenhouse gas emission. Alternative energy generation source and the improvement of energy efficiency would be largely helpful to reduce the environmental impacts on human health, ecosystem, and biodiversity. For the future environmental impact assessment based LCA works in the field of aluminum production, the cost of the production of aluminum associated with each stage should be considered which is not considered in the present study due to lack of enough information. However, this information could be added to analyze economically how the modification of the process heat generation sources or alternative routes of electricity generation could affect the environmental management system or sustainable manufacturing.

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